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# State-of-the-Art Review

## Prenatal screening and diagnosis of pulmonary artery anomalies

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### ABSTRACT

*Congenital pulmonary artery anomalies are rare. Their antenatal diagnosis requires good knowledge of fetal cardiac anatomy because their clinical presentation varies depending on the type and severity of the underlying lesion. Screening of these vascular anomalies can be straightforward in some cases, because of significant associated consequences that are detected easily on ultrasound, while other anomalies have considerably less obvious features. There may be an associated genetic syndrome. The aim of this review was to define anomalies of the main pulmonary artery and its branches and to propose, through the identification of suspicious findings during routine antenatal heart examination, an optimal screening method for the pulmonary artery pathway. We propose that pulmonary artery anomalies can be classified antenatally into four types of disorder. Herein we describe 14 cases subgrouped accordingly as: anomalies of the pulmonary valvular region, with stenosis or atresia of the valve (n=4); conotruncal abnormalities (n=4); anomalies associated with abnormal origin or pathway of the pulmonary artery (n=4); and anomalies associated with abnormal growth of the pulmonary artery and its branches (n=2). We highlight the need to differentiate the three-vessel view from the three-vessel-and-trachea view when assessing a fetus with a congenital pulmonary artery anomaly. © 2022 The Authors. *Ultrasound in Obstetrics & Gynecology* published by John Wiley & Sons Ltd on behalf of International Society of Ultrasound in Obstetrics and Gynecology.*

### INTRODUCTION

The incidence of congenital pulmonary artery (PA) anomalies varies widely: that of isolated pulmonary stenosis (PS) is approximately 1/2000 live births while

that of pulmonary agenesis is around 1/100 000 live births<sup>1–3</sup>. They are part of a heterogeneous spectrum of diseases and their antenatal diagnosis requires good knowledge of fetal cardiac anatomy because their clinical presentation varies depending on the type and severity of the underlying lesion<sup>4</sup>.

The imaging diagnosis of PA anomalies is challenging for the ultrasound practitioner, as conventional ultrasound imaging methods may have limited value in their detection and characterization. Screening can be straightforward in some cases, because of significant associated consequences that are detected easily on ultrasound, while other anomalies have considerably less obvious features<sup>5</sup>. Furthermore, they may be isolated or associated with other congenital heart defects (CHD) or genetic syndromes<sup>6</sup>. We propose that they can be classified, based on their embryological origin and from a mechanistic point of view, into four main subgroups: (1) anomalies of the pulmonary valve, (2) conotruncal anomalies, (3) abnormal origin or pathway of the PA, and (4) abnormal growth of the PA.

The aim of this illustrated review was to define anomalies of the main PA and its branches and to propose, through the identification of suspicious findings during routine antenatal heart examination, an optimal screening method for the PA pathway.

## PULMONARY ARTERY EMBRYOLOGY

### Normal pulmonary artery development

Embryonic development of the heart is a complex process that continues until the 8<sup>th</sup> week *in utero*. Its formation comprises seven main stages<sup>7</sup>: heart tube formation, cardiac looping, cardiac septation, development of the chambers and semilunar valves, development of the conduction system, development of the aortic arches (fourth arch fusing with the aorta and sixth arch fusing with the PA) and development of the pulmonary and systemic veins<sup>8,9</sup> (Figure S1).

### Development of major pulmonary artery anomalies

PA defects may result from disruption of cardiac embryogenesis during at least three of these stages: septation, development of the chambers and semilunar valves and development of the aortic arches.

### *PA anomalies related to abnormal semilunar valve development*

The formation of the pulmonary valves is one of the last steps during cardiac embryogenesis. The pulmonary

valves develop from the buds of each vessel at the junction between the conus and the truncus in the outflow tracts. The formation of the pulmonary valves involves development of the endocardial cushions and, subsequently, septation of the outflow tracts<sup>13</sup> (Figure S2). Although there are several etiologies of valve abnormality leading to PS, the most common cause is an excess of normal leaflet fusion which can lead to bicuspid arterial valves.

#### *PA anomalies related to abnormal septation of outflow tracts or conotruncal region anomalies*

To understand these PA anomalies, we should consider the developing conotruncal region (or ‘outflow tracts’) in terms of the ‘truncus’ and the ‘conus’. The truncus is the origin of the aorta and PA, while the conus represents the zone connecting the truncus and the ventricles. During development, the truncus partitions vertically (truncal septum) and then migrates forward to face the ventricular mass. The conus, by also partitioning vertically (conal septum), allows integration of the large vessels into the ventricle<sup>14</sup>. Cardiac defects resulting from abnormal development of the outflow tracts (abnormal wedging, i.e. incomplete and/or asymmetric conotruncal partitioning) include the conotruncal defects, such as tetralogy of Fallot with or without pulmonary atresia, common arterial trunk, aortopulmonary window and double-outlet right ventricle.

It has been proposed that conotruncal defects are caused by defects of the cardiac neural crest, as exemplified by ablation of premigratory neural crest cells in chicks<sup>10</sup>. However, abnormal migration of neural crest cells may not be the sole cause of abnormal conotruncal development. Following discovery of the second heart field (SHF)<sup>11</sup>, defects in its deployment are now considered to be a major cause of structural CHD, including conotruncal defects. During cardiac embryogenesis, the early-differentiating cells of the first heart field contribute to the left ventricle and parts of the left atrial myocardium, while the SHF drives growth of the heart by progressive addition of cardiomyocytes, giving rise to the right ventricle, outflow tracts and atrial septal structures<sup>11</sup>. In animal models, it has been shown that impaired SHF development results in a spectrum of defects in cardiac morphogenesis, including absence of SHF, absence of heart tube elongation, wedging and failure of cardiac looping, resulting in early embryonic laterality abnormalities<sup>12</sup>. Less severe perturbation of SHF development results in alignment defects of the great arteries during cardiac septation, including tetralogy of Fallot and pulmonary atresia.

#### *PA anomalies related to abnormal development of the aortic arches*

During embryogenesis, the aortic arches are transient bilateral bulges that develop in the cranial region of the embryo. Each arch has an external layer of ectoderm and an inner layer of endoderm, and in between these are mesenchymal neural-crest-derived cells surrounding

a mesodermal core. Embryonic development of the aortic arches, from which the PAs arise, is intricate and complex, and there are many opportunities for disruption during their development. Involvement of the cardiac neural crest cells, a subgroup of neural crest cells arising from the postotic hindbrain, in the development of the aortic arches and subsequent great arteries has been well documented by neural crest ablation experiments in animal models<sup>10</sup>. The six aortic arches appear sequentially, not simultaneously, in a craniocaudal order. The first and second aortic arches develop mainly into skeletal elements, the third becomes the common carotid artery, the fourth forms the arch of the aorta, the fifth generally degenerates (its persistence is exceptional) and the sixth forms the arterial duct and the initial part of the central PAs. Normal embryogenesis of the aortic arches plays a major role in the formation of the large vessels and also in the separation of the initially common arterial trunk into the ascending aorta and the PA. Any abnormality in the formation of the aortic arches can lead to abnormal origin of the PA (Figure S3).

#### *PA anomalies related to abnormal growth of the PA*

Growth of the PA may manifest as PA hypoplasia or agenesis. PA hypoplasia may be isolated or be part of a more complex entity, such as scimitar syndrome (consisting of hypoplasia of one pulmonary branch, abnormal partial pulmonary venous return and pulmonary sequestration).

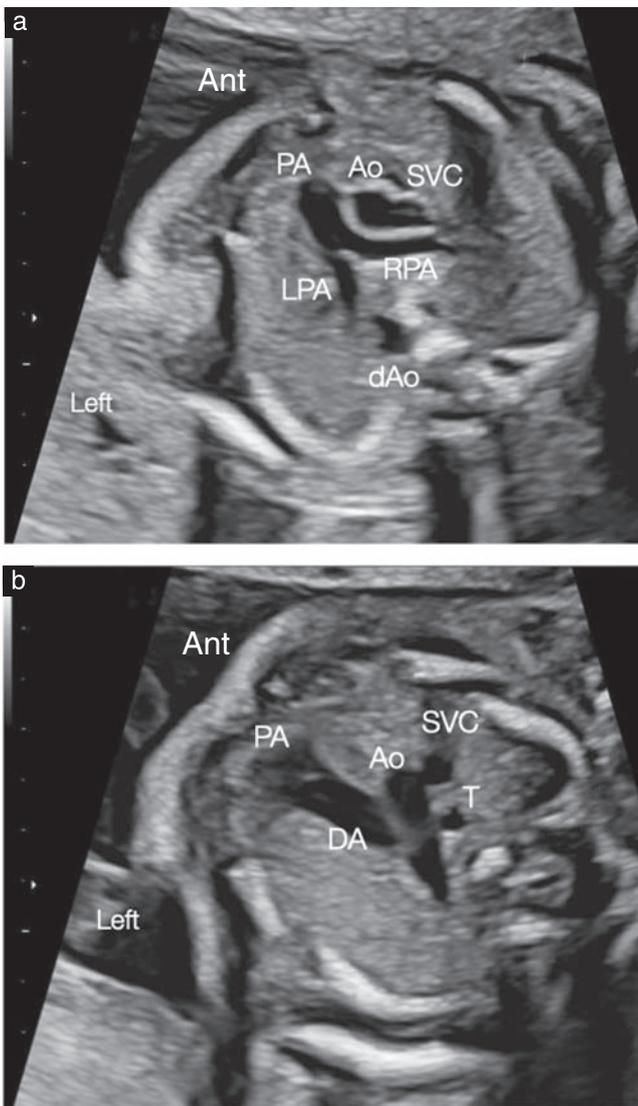
## SCREENING AND DIAGNOSIS OF PULMONARY ARTERY ABNORMALITIES

### Screening for pulmonary artery abnormalities

Prenatal detection of PA anomalies decreases neonatal mortality when compared with postnatal detection, as fetuses with these critical lesions should be delivered at tertiary care centers and often require immediate neonatal intensive care, especially in case of ductal-dependent conditions<sup>15</sup>. French national guidelines<sup>16</sup> as well as the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG)<sup>17</sup> and the American Institute of Ultrasound in Medicine (AIUM)<sup>18</sup> guidelines related to screening ultrasound in pregnancy agree regarding the need to perform a fetal anatomical survey as early as possible, with a cardiac evaluation of the four-chamber view (4CV) and the outflow tracts. The use of color Doppler depends on the context of the examination (screening *vs* fetal echocardiography)<sup>17</sup>. The main PA or pulmonary trunk trifurcates into the ductus arteriosus and the right (RPA) and left (LPA) PAs, and should always be assessed on ultrasound using three main views: the three-vessel (3V) and three-vessel-and-trachea (3VT) views, a short-axis view at the level of the aortic root and a parasagittal view through the right ventricular outflow tract (RVOT).

In the normal fetus, the 3V view<sup>19,20</sup>, described by Yoo *et al.*<sup>21</sup> in 1997, displays simultaneously the origin

of the pulmonary trunk, located anterior and to the left of the aorta, along with the ascending aorta and superior vena cava. The confluence of the LPA and RPA can be seen arising from the pulmonary trunk. Sweeping a little higher, from the fetal abdomen towards the chest, it is possible to obtain the 3VT view, described by Yagel *et al.*<sup>22</sup> in 2002. In this view, it is not possible to assess both PAs, but, in a normal fetus, both the ductal and aortic arches should be displayed. These arches, when present and normal, form an inverted ‘Y’ shape (Figures 1–3). It is necessary to differentiate the 3V view (Figure 1a) from the 3VT view (Figure 1b)<sup>21,22</sup>. Two variations of the 3V and 3VT views are now recognized by the collaborative fetal echocardiography guidelines, one which demonstrates the main PA bifurcation and another (superiorly) that demonstrates the PA and the ductal arch<sup>23</sup>.

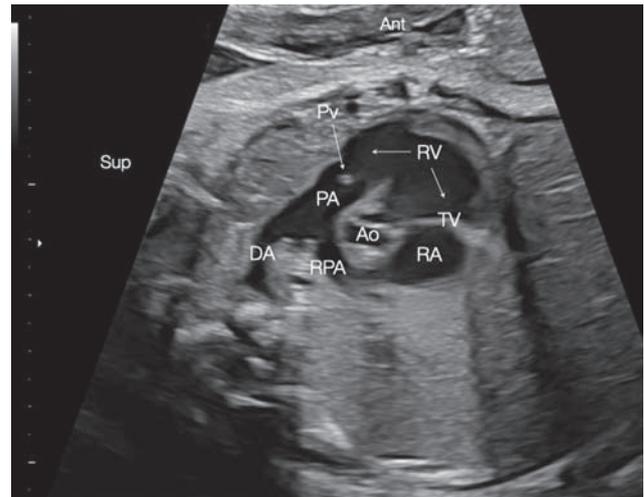


**Figure 1** Normal axial view of the great vessels (23 weeks' gestation). (a) Three-vessel view showing division of trunk of pulmonary artery (PA) into left pulmonary artery (LPA) and right pulmonary artery (RPA). (b) Three-vessel-and-trachea (3VT) view showing, from left to right, PA, ductus arteriosus (DA), aorta (Ao) and its horizontal and isthmal parts, to left of trachea (T), and superior vena cava (SVC). Ant, anterior; dAo, descending aorta.

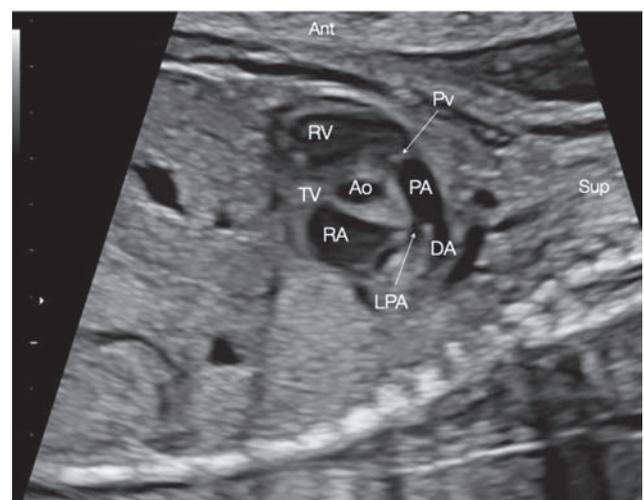
A short-axis view at the level of the aortic root allows mapping of the RVOT: the root of the PA with its leaflets; the pulmonary trunk; and the ductus arteriosus as it runs posteriorly towards the spine and the RPA (Figure 2).

A parasagittal view through the RVOT demonstrates: the pulmonary valve leaflets; the pulmonary trunk; the ductus arteriosus, which is wider and flatter than the aortic arch, has no head and neck vessels arising from it and joins the isthmic part; the descending aorta; and the LPA (Figure 3).

There are several ways to identify PA anomalies on screening ultrasound, and the use of pulsed-wave



**Figure 2** Normal short-axis view (23 weeks' gestation) at level of aortic root, which allows mapping of right ventricular outflow tract: root of pulmonary artery (PA) with leaflets (or 'pulmonary valve' (Pv)), pulmonary trunk and ductus arteriosus (DA) as it runs posteriorly towards spine and right pulmonary artery (RPA). Ant, anterior; Ao, aorta; RA, right atrium; RV, right ventricle; Sup, superior; TV, tricuspid valve.



**Figure 3** Normal parasagittal view through right ventricular outflow tract (23 weeks' gestation). Ant, anterior; Ao, aorta; DA, ductus arteriosus; LPA, left pulmonary artery; PA, pulmonary artery; Pv, pulmonary valve; RA, right atrium; RV, right ventricle; Sup, superior; TV, tricuspid valve.

and color Doppler is necessary in their assessment and diagnosis. PA anomalies are rarely identified by direct visualization of the primary anomaly; rather, they are identified mostly indirectly by visualization of their consequences, such as abnormalities of cardiac position related to global shifting and/or axis deviation, global or focal enlargement of the fetal heart dimensions, or other

consequences in the structures surrounding the PA and its branches, including myocardial thickening, dilation and hypokinesia. According to the type of anomaly, it is possible for the 3V and 3VT views to differ such that a normal 3V view may be associated with an abnormal 3VT view (e.g. aortopulmonary window) or an abnormal 3V view with a normal 3VT view (e.g. abnormal origin

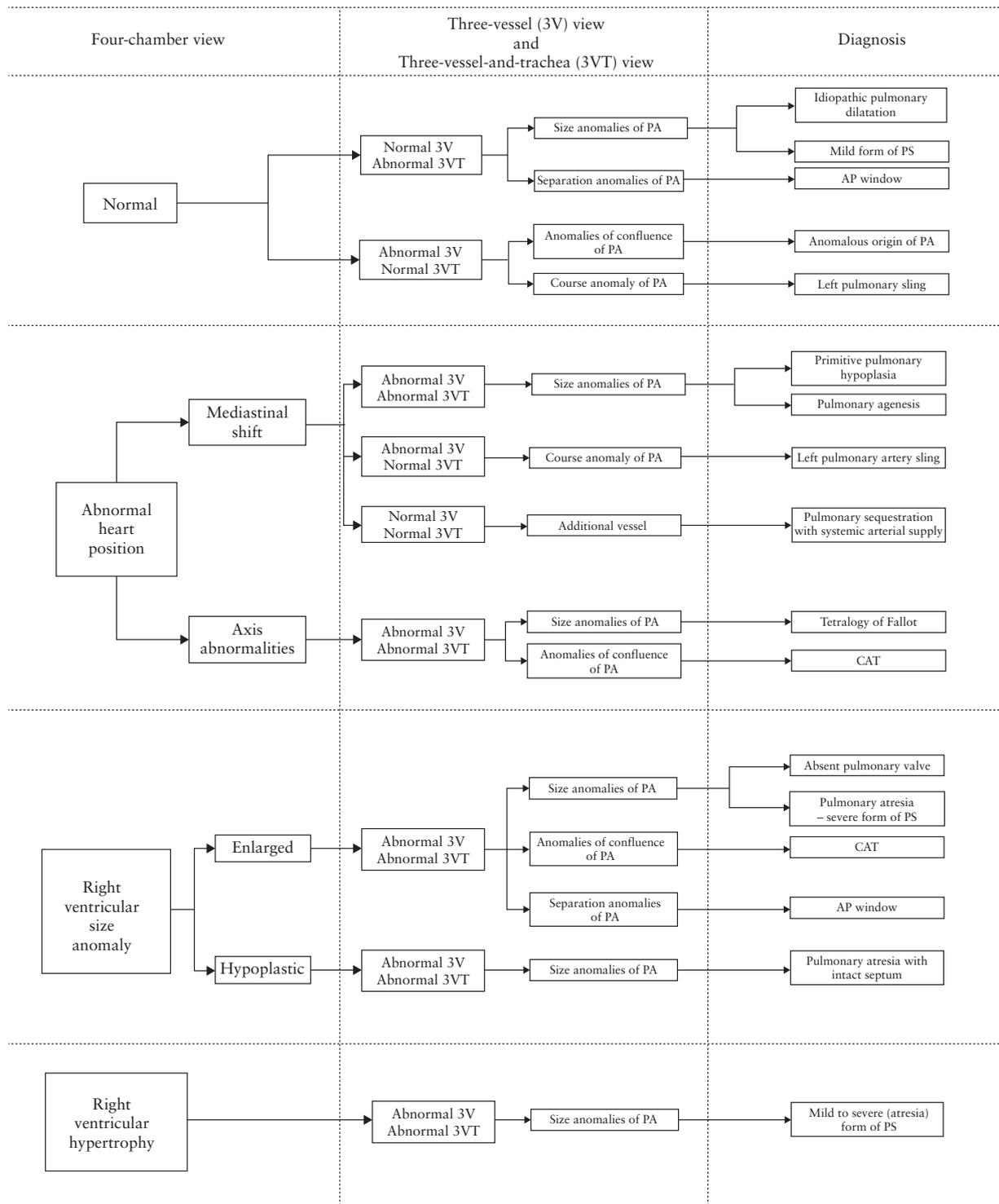


Figure 4 Flow chart showing diagnostic algorithm according to different forms of pulmonary artery (PA) anomaly. AP, aortopulmonary; CAT, common arterial trunk; PS, pulmonary stenosis.

of one PA or left pulmonary sling) (Table S1). According to the published guidelines<sup>16–18</sup> and from a theoretical perspective, it is always necessary, and possible, to pick up all of these major indirect signs. Herein, therefore, we propose a diagnostic algorithm for PA anomalies

**Table 1** Summary of congenital pulmonary artery anomalies, grouped into our proposed four types of disorder

Anomaly of pulmonary valvular region (pulmonary stenosis)	
Subvalvular:	
Infundibulum: tetralogy of Fallot, recipient in twin-to-twin transfusion syndrome	
Valvular:	
Non-dysplastic and fused valves (most common)	
Dysplastic and non-fused valves (Noonan syndrome)	
Supravalvular (rarely seen in antenatal period):	
Alagille syndrome, Williams–Beuren syndrome, Ehlers–Danlos disease, post-rubella syndrome	
Conotruncal anomalies (often associated with VSD with or without anterior malalignment)	
Tetralogy of Fallot (infundibular stenosis):	
Mild → moderate → severe stenosis (pulmonary atresia)	
Absence of pulmonary valves	
Common arterial trunk	
Aortopulmonary window (no VSD)	
Abnormal origin or pathway of pulmonary artery	
Abnormal origin of one pulmonary artery (RPA more frequently than LPA)	
Pulmonary artery sling	
Additional lung systemic feeding vessel(s) (MAPCA, sequestration)	
Abnormal growth of pulmonary artery	
Unilateral lung agenesis (atresia of one pulmonary artery)	
Pulmonary hypoplasia (hypoplasia of one pulmonary artery with or without scimitar syndrome)	

LPA, left pulmonary artery; MAPCA, major aortopulmonary collateral artery; RPA, right pulmonary artery; VSD, ventricular septal defect.

(Figure 4). Some diagnoses may have several warning signs. For clarity, 3V and 3VT view abnormalities have been classified together as anomalies of: size, confluence, course, separation and additional vessel(s) (Figure 4).

## Diagnosis of pulmonary artery abnormalities

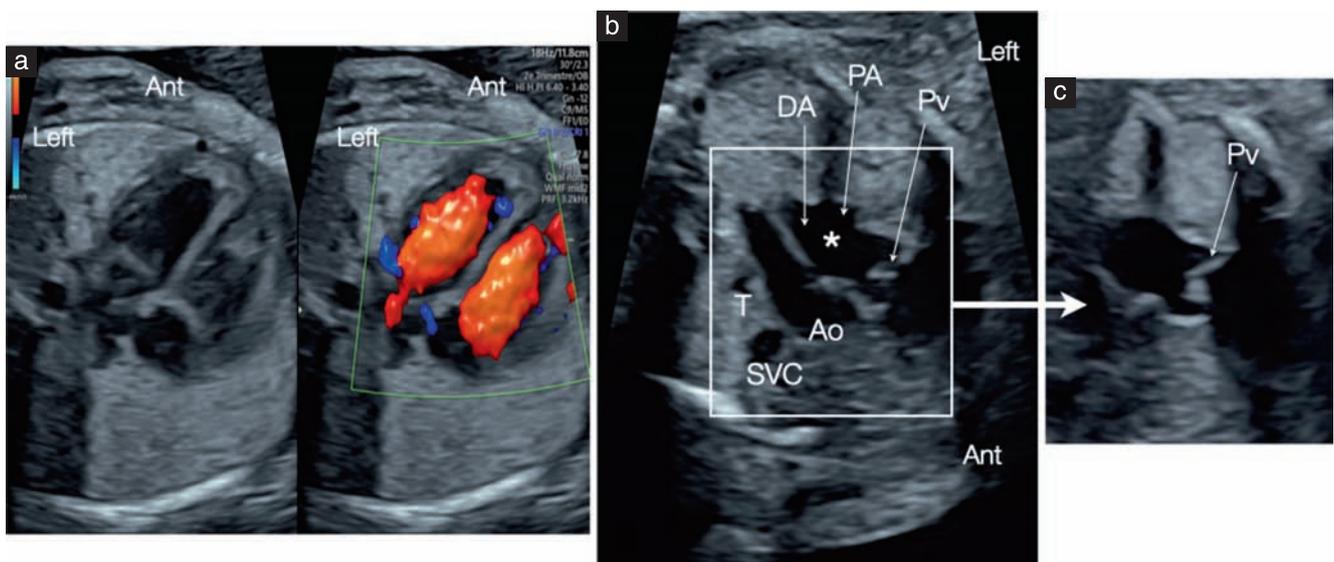
### Main anomalies of the PA

There are many different anomalies of the PA pathway. The key to overcoming the complexity of the diagnosis lies in having a logical approach, analyzing the valvular region in order to distinguish pulmonary valve anomalies, the RVOT in order to distinguish conotruncal anomalies, and the pulmonary branches in order to distinguish abnormalities in branch size and/or position. Table 1 presents a summary of PA anomalies.

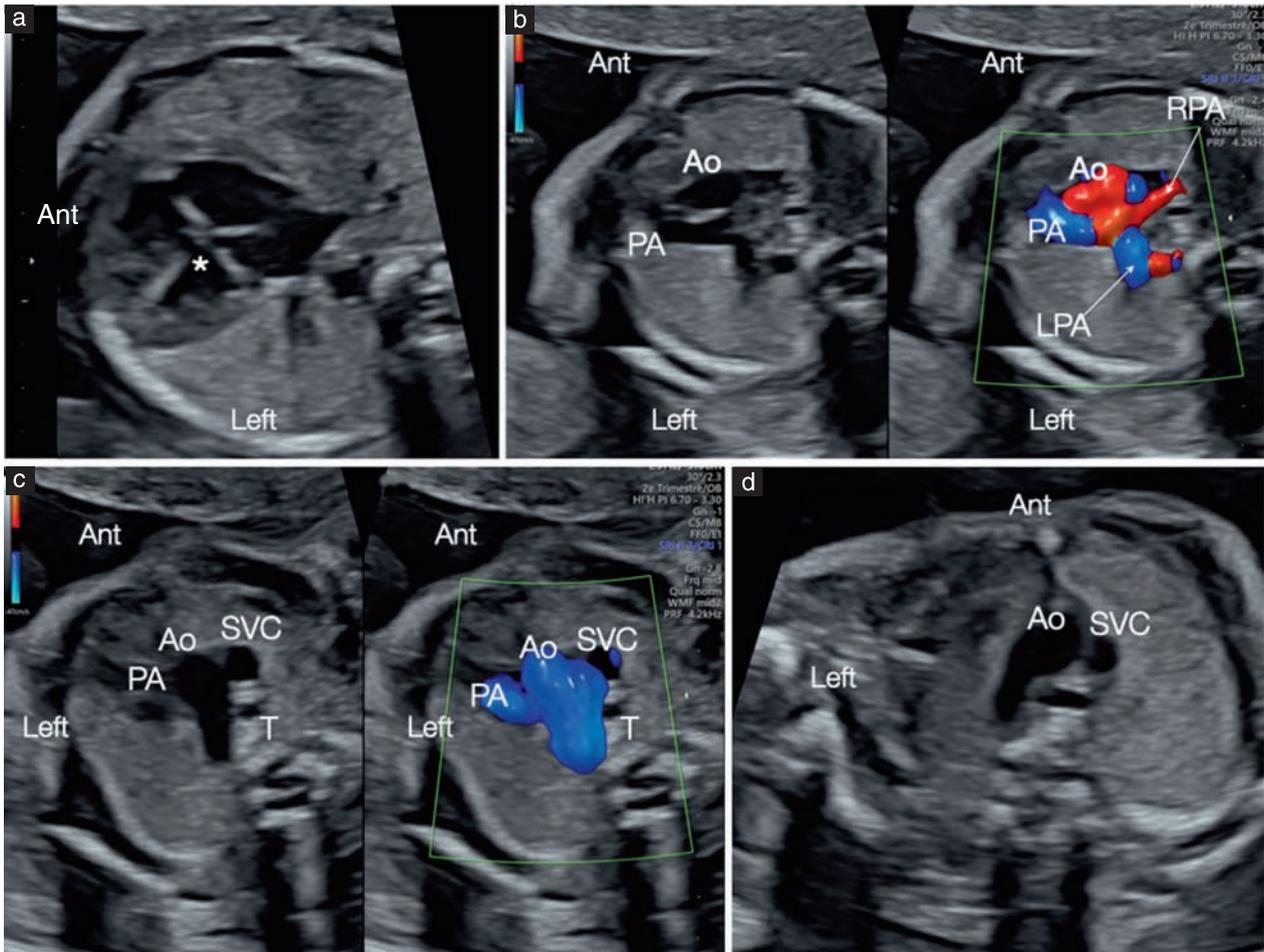
### Pulmonary stenosis

Congenital PA anomalies comprise a heterogeneous spectrum of disease, ranging from subtle, isolated PS to complete pulmonary agenesis. Although it is not currently recommended to examine the PA valves during antenatal ultrasound screening, PS is relatively common, accounting for 8–12% of all congenital heart defects in children<sup>24</sup>. The most common form of PS is a dome-shaped pulmonary valve, resulting in enlargement of the pulmonary trunk and, in some cases, dilation of the LPA due to regurgitation.

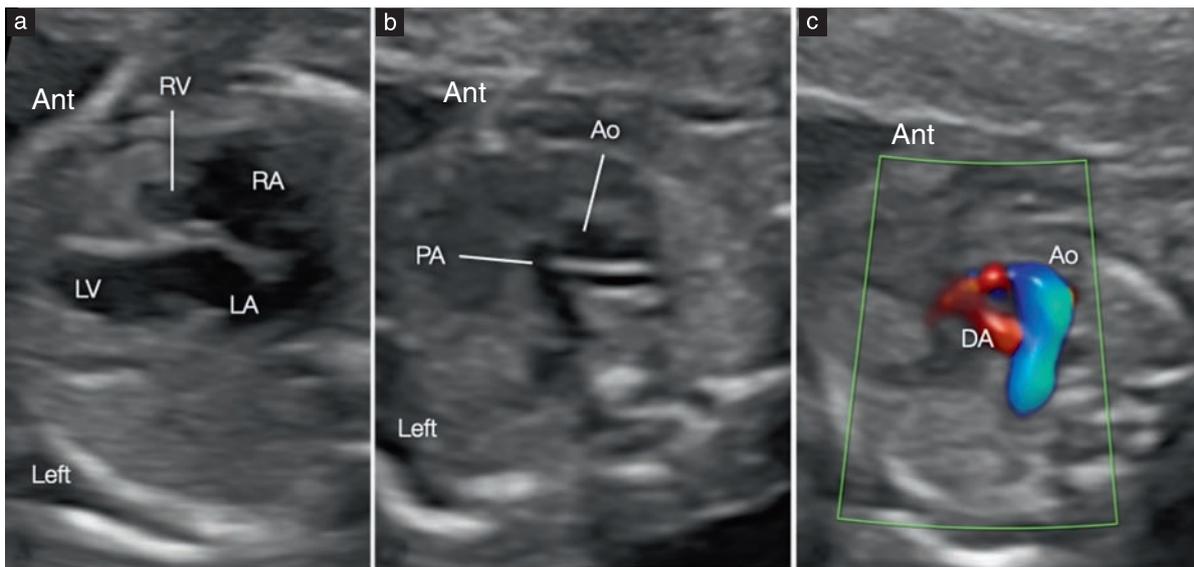
PS encompasses a spectrum of anomalies, which should be differentiated, according to the affected valve region, into subvalvular, valvular and supravalvular anomalies. Subvalvular anomalies are frequently found in tetralogy of



**Figure 5** Imaging in 26-week fetus with mild pulmonary stenosis. (a) Four-chamber view appears normal. (b) Three-vessel-and-trachea view appears normal, but, on closer inspection, ductus arteriosus (DA) in continuity with pulmonary artery (PA) appears slightly larger than aorta (Ao), with slight dilation (\*). (c) Pulmonary valves (Pv) appear hyperechoic, thicker and dome-shaped, with a narrow opening reflecting pulmonary valve dysplasia and a probable stenosis suggested by characteristic post-stenotic dilation. Ant, anterior; SVC, superior vena cava; T, trachea.



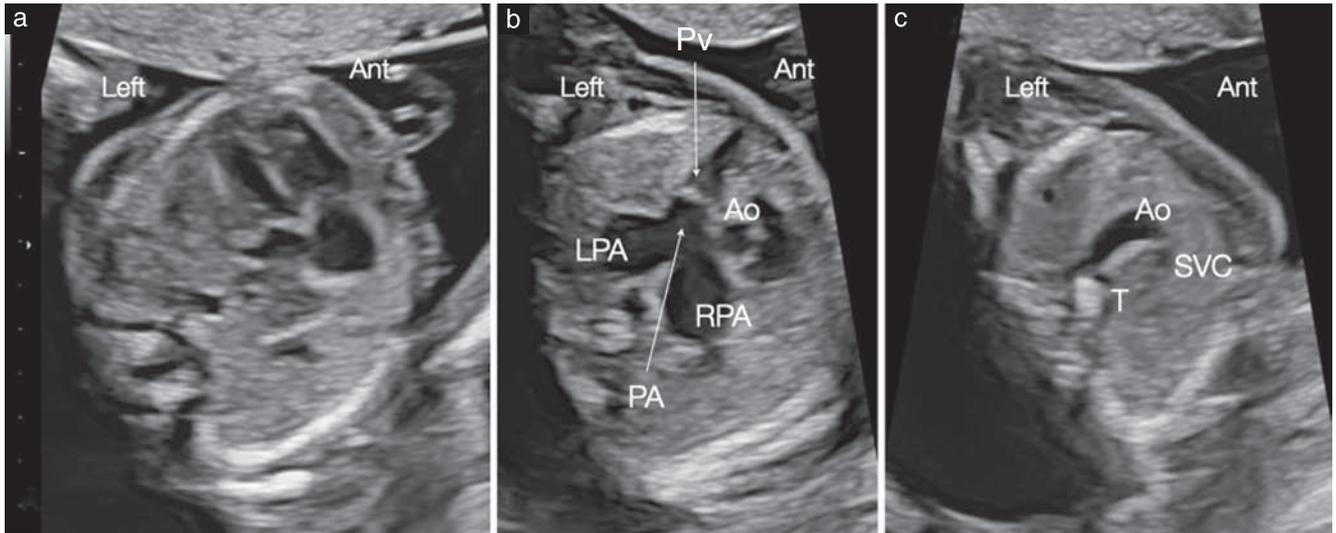
**Figure 6** Imaging in 23-week fetus with moderate pulmonary stenosis and tetralogy of Fallot. (a) Four-chamber view is abnormal, with levocardia and ventricular septal defect (\*). (b) Three-vessel view (shown without and with color Doppler) is abnormal, with asymmetry between pulmonary artery (PA) and Aorta (Ao), such that PA diameter < Ao diameter. (c,d) Three-vessel-and-trachea view is also abnormal, showing similar asymmetry (PA diameter < Ao diameter) (shown without and with color Doppler) (c), and ductus arteriosus cannot be displayed. Ant, anterior; LPA, left pulmonary artery; RPA, right pulmonary artery; SVC, superior vena cava; T, trachea.



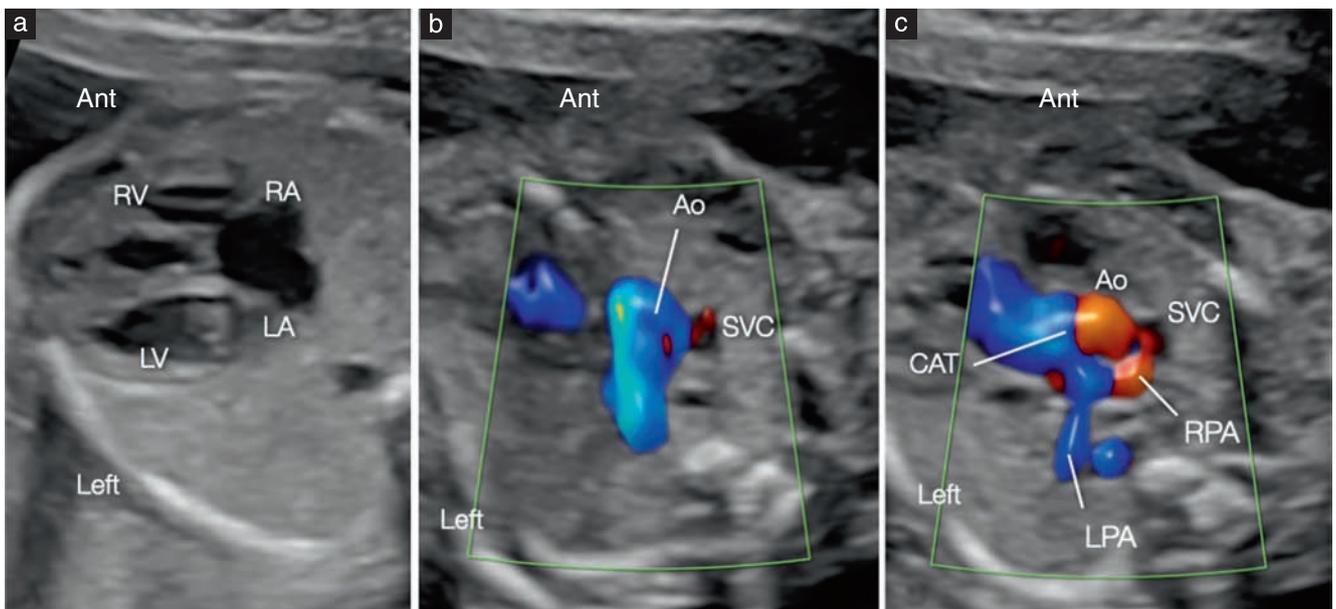
**Figure 7** Imaging in 18-week fetus with pulmonary atresia with intact septum. (a) Associated small and hypertrophied right ventricle (RV), with normal right atrium (RA) and normal left ventricle (LV) and left atrium (LA) are seen in four-chamber view. (b) In three-vessel view, pulmonary artery (PA) and its branches are small. (c) In three-vessel-and-trachea view, aorta (Ao) is enlarged and there is retrograde flow in ductus arteriosus (DA). Ant, anterior.

Fallot and are seen in 6–13% of recipient twins in cases of twin-to-twin transfusion syndrome<sup>25</sup>. In valvular anomalies, it is necessary to differentiate fused and non-dysplastic valves (the most frequent type) from non-fused and dysplastic valves, which can be found in RASopathies, such as Noonan syndrome (estimated incidence of Noonan syndrome, 1 in 1000–2500 live births) and cardiofaciocutaneous and related syndromes<sup>26,27</sup>. Supravalvular anomalies are rarely seen prenatally, but, postnatally, are frequently found in Alagille, Williams–Beuren, post-rubella and Ehlers–Danlos syndromes<sup>28</sup>.

Although, generally, it is the indirect signs (anomalies of the 4CV, RVOT view and/or 3V and/or 3VT views) that alert the practitioner, some PA anomalies can be picked up directly. In fact, mild forms of isolated PS without any consequences in the right ventricle can only be diagnosed directly by visualization of thickening and dysplasia of the pulmonary valve leaflets throughout the cardiac cycle, or indirectly by visualizing post-stenotic dilatation at the origin of the main PA. Thus, if PS is suspected, regardless of the type, a thorough assessment should be carried out using both pulsed and color Doppler.



**Figure 8** Imaging in 19-week fetus with absent/dysplastic pulmonary valve (Pv). (a) Associated enlarged right ventricle and levo-cardia is evident in four-chamber view. (b) In three-vessel view can be seen significant dilatation of right (RPA) and left (LPA) pulmonary arteries. (c) In three-vessel-and-trachea view, ductus arteriosus is not seen, with visualization only of aorta (Ao) and superior vena cava (SVC). Ant, anterior; PA, pulmonary artery; T, trachea.



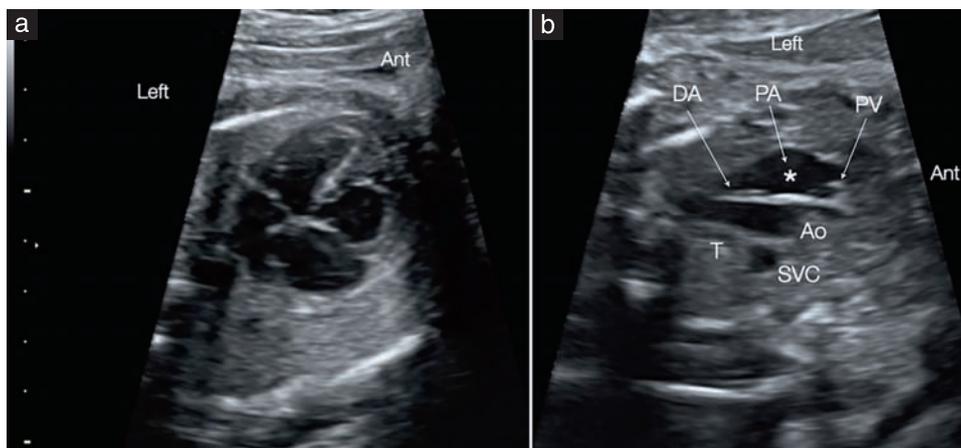
**Figure 9** Imaging in 23-week fetus with common arterial trunk (CAT). (a) Four-chamber view is normal. (b) Three-vessel-and-trachea view on color Doppler imaging is abnormal, with visualization of only one great vessel (aorta (Ao)) and superior vena cava (SVC). (c) Three-vessel view on color Doppler imaging displays CAT with origins of right (RPA) and left (LPA) pulmonary arteries in its posterior part. Ant, anterior; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

whether there is associated pulmonary and/or tricuspid regurgitation, reversed flow into the ductus arteriosus and abnormal blood flow in the ductus venosus. PS can be diagnosed during pregnancy (from the early second trimester onwards) or after delivery. The challenge in diagnosis lies mainly in the many and varied clinical presentations<sup>28</sup>.

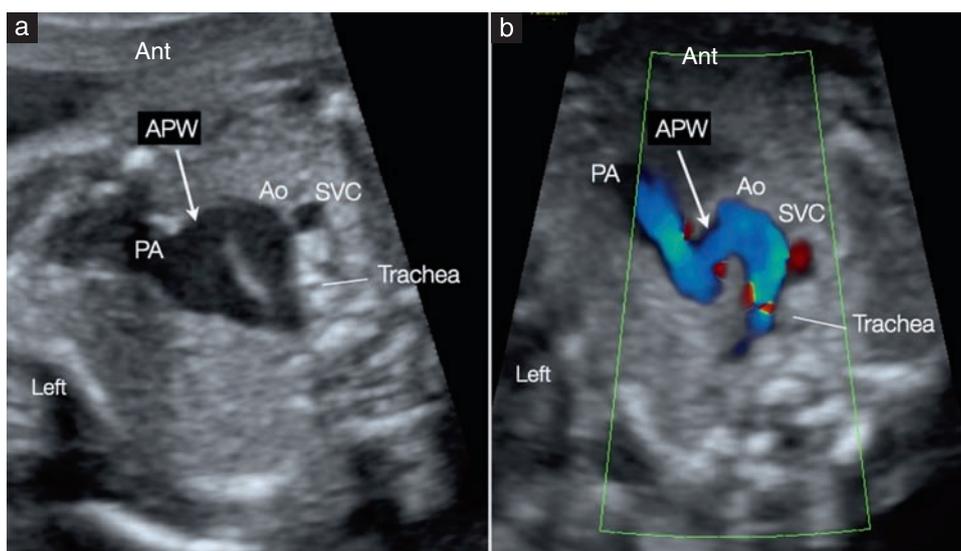
### Cardiac MRI

Cardiac magnetic resonance imaging (MRI) may be an attractive option for assessing PA anomalies as an alternative or complementary technique, particularly given the lack of ionizing radiation<sup>29</sup>. However, there are practical

heart rate of the human fetus, the lack of conventional methods with which to synchronize data acquisition and the potential corruption of MRI data due to unpredictable fetal movements and maternal respiration<sup>30</sup>. Its application in the evaluation of fetal PAs is under-researched and further work is required to clarify its usefulness. Similarly, the use of 3D/4D ultrasound (spatiotemporal image correlation (STIC) technology) may be of interest, but it remains to be demonstrated whether this technique offers any additional value in this particular condition. Antenatal cardiac MRI may also be useful for second-line non-invasive exploration of congenital PA disease, especially for assessing the consequences to the lungs that may be associated with these anomalies<sup>30</sup>.



**Figure 10** Imaging in 24-week fetus with idiopathic pulmonary dilatation. (a) Four-chamber view is normal. (b) Relationship between vessels in three-vessel-and-trachea view is normal, but there is enlargement (\*) of pulmonary artery (PA). This diagnosis is by exclusion; it is necessary to exclude pulmonary valve (PV) stenosis and diagnostic elements of Marfan disease. Until full postnatal assessment, this could be mistaken for mild pulmonary valve stenosis. It should prompt postnatal evaluation throughout infancy. Ant, anterior; Ao, aorta; DA, ductus arteriosus; SVC, superior vena cava; T, trachea.



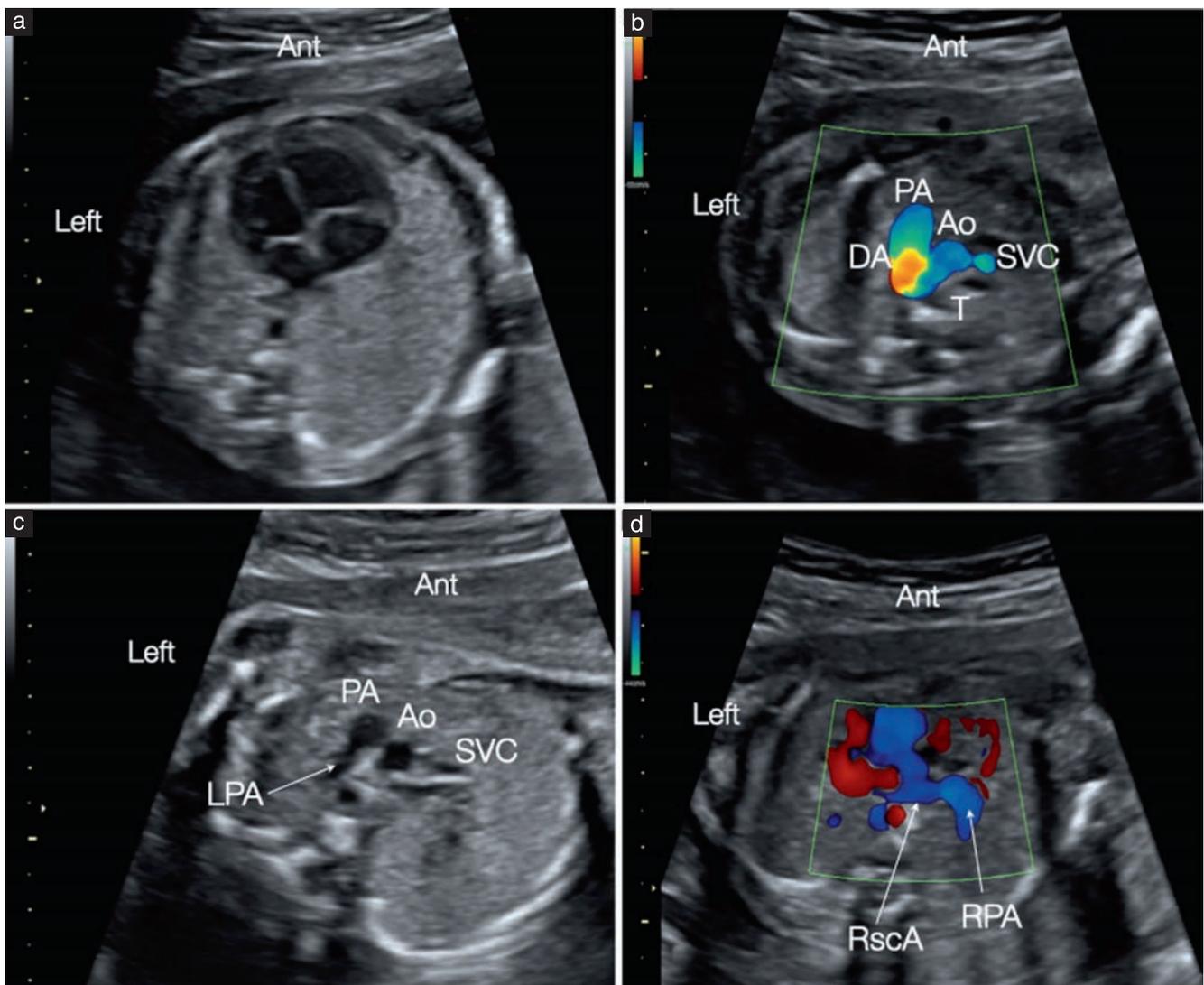
**Figure 11** Imaging in 31-week fetus with aortopulmonary window (APW). (a) Three-vessel-and-trachea view is abnormal. Relationship between the three vessels is normal, but defect is evident between pulmonary artery (PA) and ascending aorta (Ao), which is also seen on color Doppler imaging (b). Ductus arteriosus is normal in this case, but can be hypoplastic or absent. Ant, anterior; SVC, superior vena cava.

## CASE SERIES

Various types of congenital anomaly may affect the PAs. We present herein, drawn from a 10-year retrospective database review, several examples of anomalies of the main PA and its branches. We describe each type of anomaly, the usual point in pregnancy at which it is detected, the typical ultrasound features on each recommended view (4CV, RVOT, 3V view and 3VT view), the contribution of cardiac MRI, the genetic examinations that may be performed and the neonatal prognosis. All cases were examined by an expert practitioner (R.C. or E.Q.). All patients were referred for suspected anomalies in the 4CV and/or outflow tracts. All sonographic examinations were performed using a transabdominal approach using a GE Voluson Expert or a Voluson E10 (GE Healthcare, Zipf, Austria) ultrasound machine, equipped with a multifrequency transabdominal probe.

In Table S1, we describe each of 14 types of anomaly, illustrating them with a clinical case, with emphasis on their sonographic appearance and the likely neonatal outcome. We chose to exclude abnormalities of the ductus arteriosus, such as right and double ductus arteriosus, and to focus on those of the PAs, i.e. the trunk and its branches. Absence of the ductus arteriosus (e.g. in common truncus arteriosus or in absent pulmonary valve syndrome) has been described in association with PA anomalies but it cannot be classified as a PA anomaly in its own right.

The 14 different prenatally diagnosed cases of PA anomaly were selected in order to represent particular subgroups of our proposed four main families of disorder: (1) anomaly of the pulmonary valvular region, (2) conotruncal anomaly, (3) abnormal origin or pathway of the PA and (4) abnormal growth of the PA. Anomalies of the pulmonary valvular region with stenosis or atresia of the valve included: mild form of isolated PS (Figure 5);



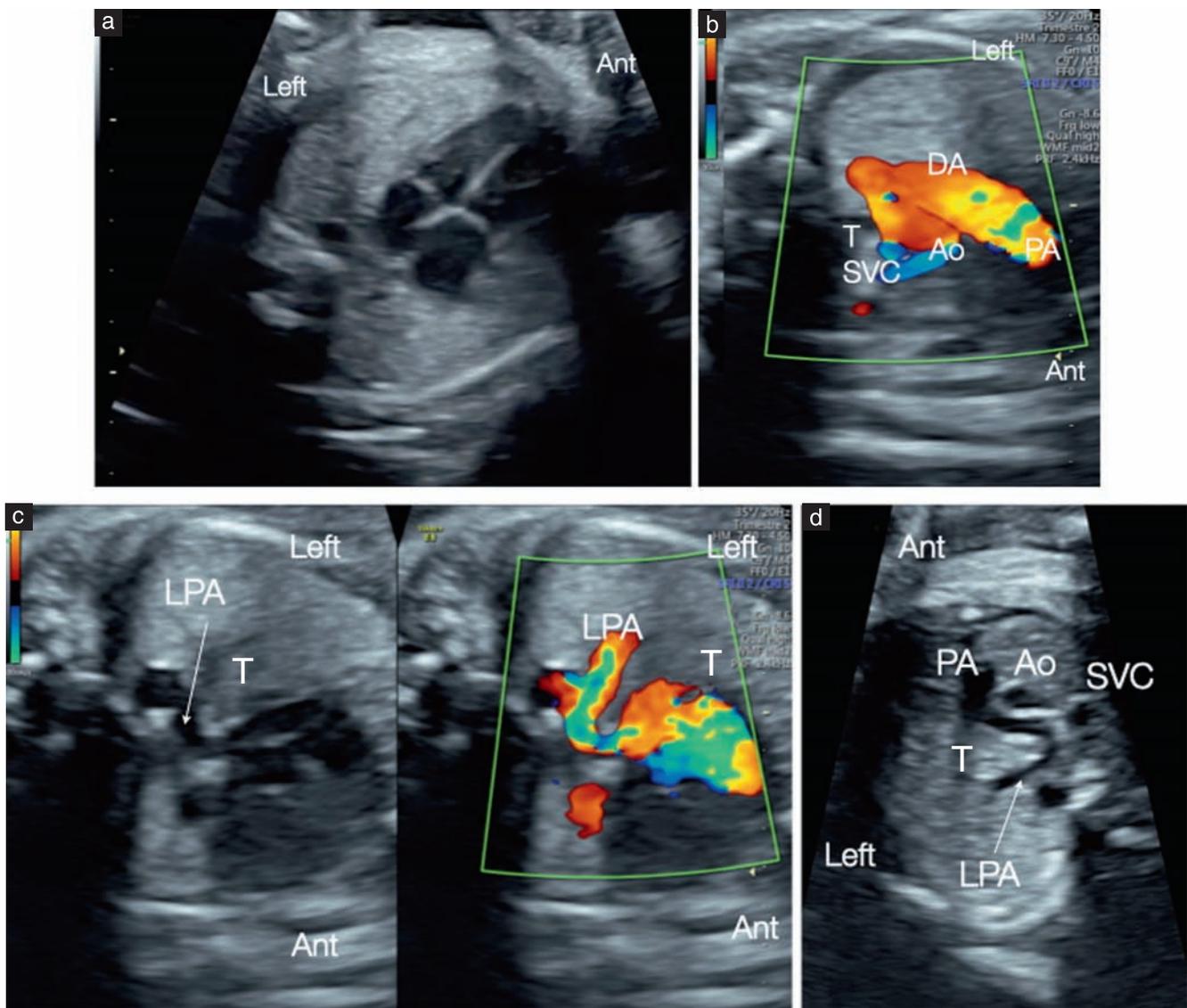
**Figure 12** Imaging in 22-week fetus with anomalous origin of pulmonary artery. Four-chamber view (a) and three-vessel-and-trachea view (b) are normal. (c) In three-vessel view, only start of left pulmonary artery (LPA) is visualized, with bifurcation of pulmonary arteries. This finding is very subtle; it is easy to misdiagnose this condition. (d) Right pulmonary artery (RPA) is seen arising from right subclavian artery (RscA). Ant, anterior; Ao, aorta; DA, ductus arteriosus; PA, pulmonary artery; SVC, superior vena cava; T, trachea.

tetralogy of Fallot with mild PS, moderate PS (Figure 6) or severe PS with ventricular septal defect (VSD); and pulmonary atresia with intact septum (Figure 7). Conotruncal anomalies included: absent pulmonary valve syndrome (Figure 8) with or without VSD; common arterial trunk (Figure 9); idiopathic pulmonary dilatation (Figure 10); aortopulmonary window (Figure 11); and an anomaly from the spectrum of tetralogy of Fallot with an outlet VSD with anteriorly malaligned outlet septum. Anomalies associated with abnormal origin or pathway of the PA included: anomalous origin of the PA (Figure 12); LPA sling (Figure 13); and two different conditions with additional pulmonary feeding vessels, one in the setting of pulmonary sequestration and one in the setting of tetralogy of Fallot with pulmonary atresia, VSD and major aortopulmonary collateral arteries (MAPCAs) (Figure 14). Abnormal growth of the PA included:

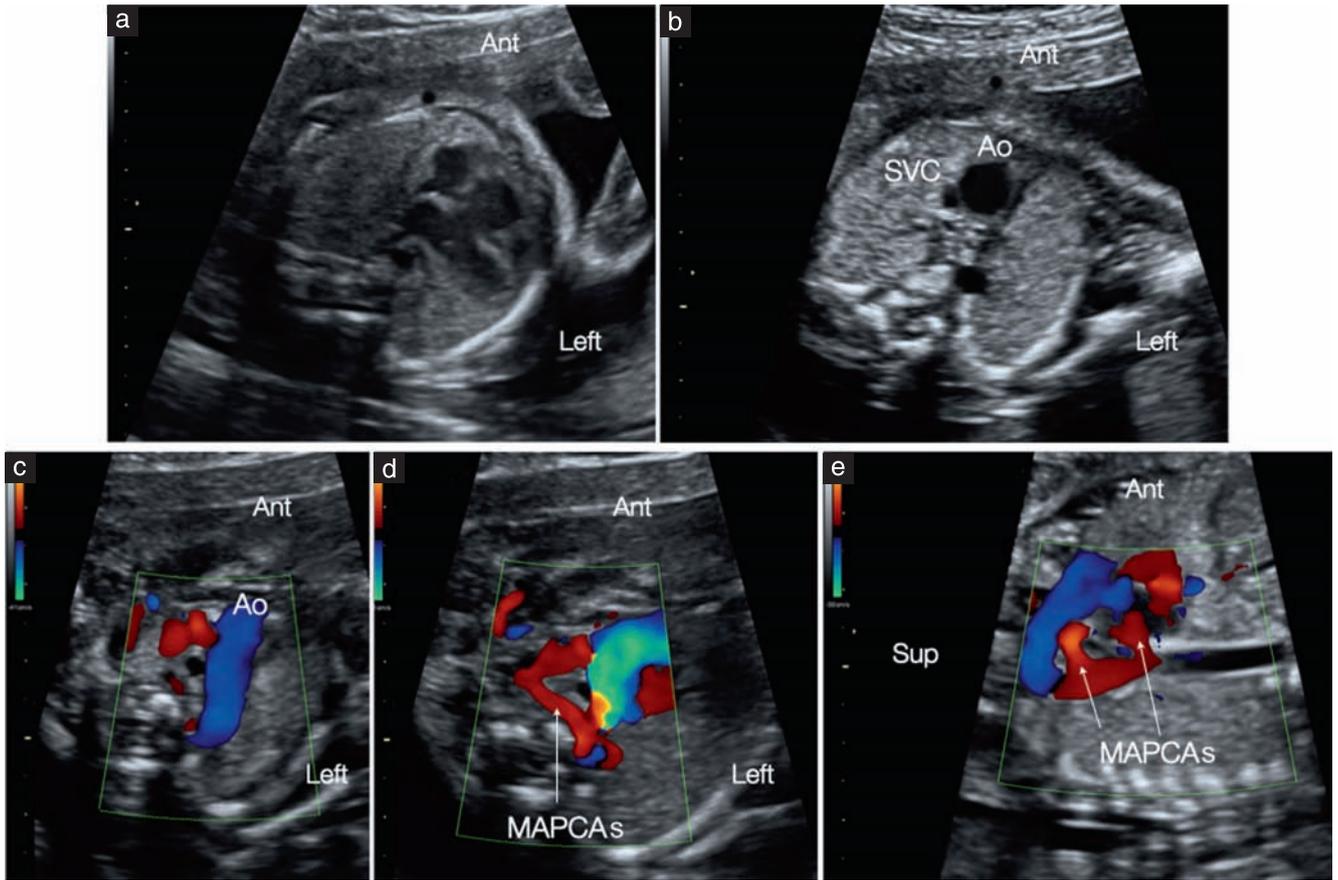
pulmonary agenesis (Figure 15); and primitive pulmonary hypoplasia (Figure 16). (It is necessary to differentiate primary from secondary hypoplasia, which may occur in some cases of congenital diaphragmatic hernia or in some of prolonged premature rupture of the membranes.)

## CONCLUSION

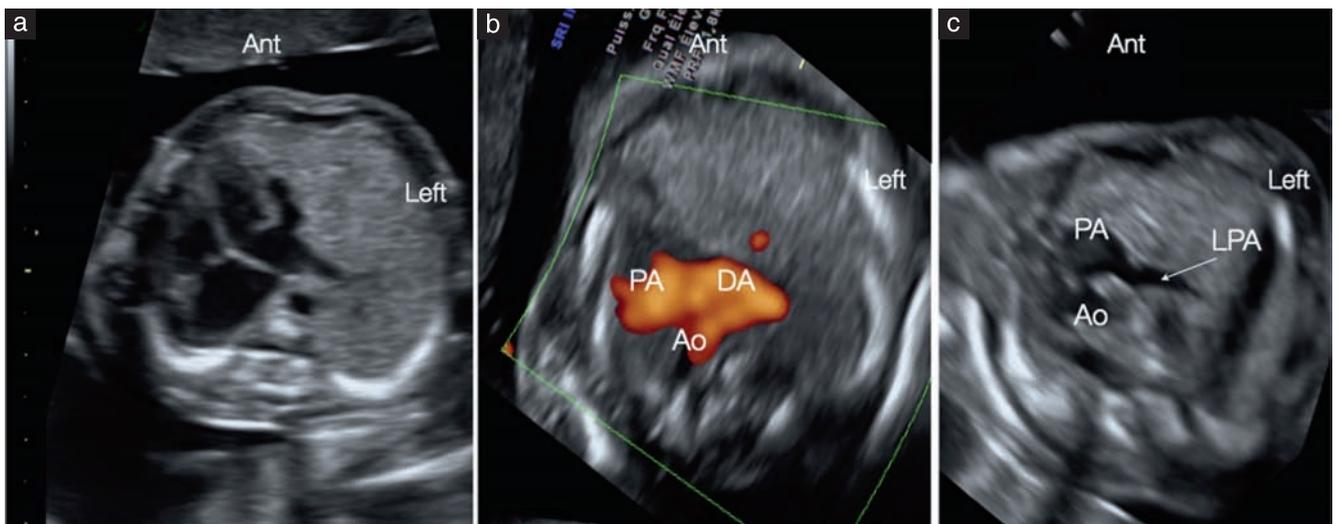
In summary, a good knowledge of the whole spectrum of PA anomalies could improve antenatal screening and allow better coordination in the management of these patients, targeted to the type of associated malformation, especially for neonates with critical or ductal-dependent cardiac lesions. Accurate prenatal diagnosis of PA anomalies ensures delivery at a tertiary hospital where it is possible to perform critical interventions (e.g. catheter and/or surgery) and stabilize the neonate if necessary. To



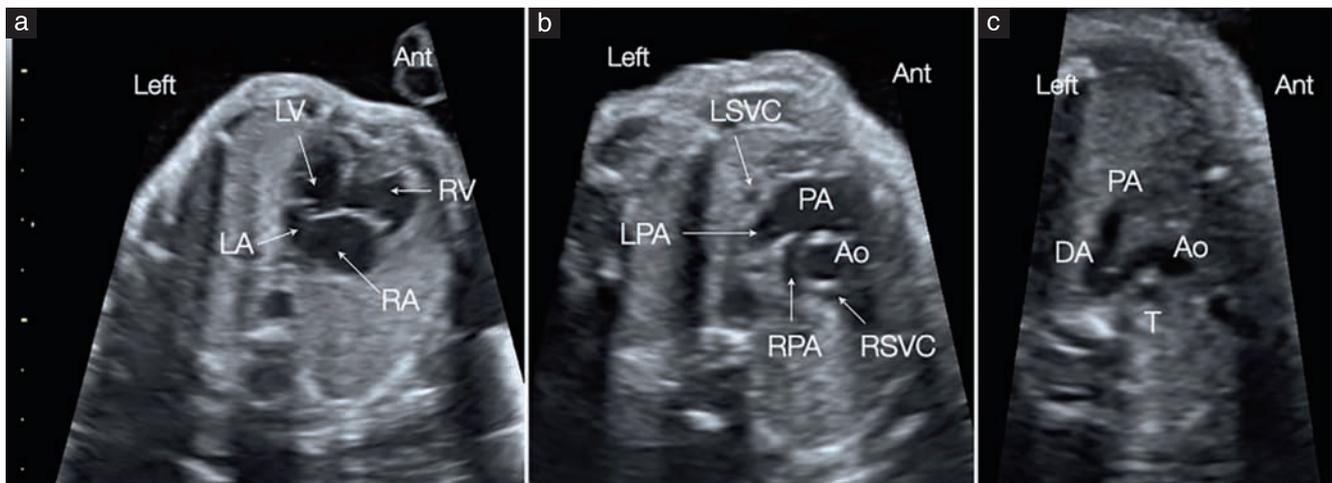
**Figure 13** Imaging in 26-week fetus with left pulmonary artery (LPA) sling. (a) Four-chamber view appears normal. (b) In three-vessel-and-trachea view, confluence and size of vessels are normal. (c,d) Visible only in three-vessel view, aberrant LPA (c), coursing between trachea (T) and esophagus, just behind left bronchus, confirms existence of sling (d). Ant, anterior; Ao, aorta; DA, ductus arteriosus; PA, pulmonary artery; SVC, superior vena cava.



**Figure 14** Imaging in 23-week fetus with severe form of tetralogy of Fallot with pulmonary atresia with ventricular septal defect. (a) Four-chamber view shows mild right ventricular hypertrophy with levocardia. (b,c) In three-vessel view, trunk of pulmonary artery and its branches appear atretic, giving impression of enlarged aorta (Ao), next to superior vena cava (SVC). Major aortopulmonary collateral arteries (MAPCAs) can be visualized in axial (d) and parasagittal (e) views. Ant, anterior; Sup, superior.



**Figure 15** Imaging in 23-week fetus with right pulmonary agenesis. (a) In four-chamber view, heart completely fills right hemithorax. (b,c) Both three-vessel (3V) view and three-vessel-and-trachea (3VT) view are rotated in order to display them in the same axis as the four-chamber view, positioning the spine at 6 o'clock. In 3VT view (b), a change in orientation of ductus arteriosus (DA) and aorta (Ao) is evident, both vessels being deviated to the right. (c) In 3V view, only left pulmonary artery (LPA) arising from pulmonary artery (PA) is visualized. Ant, anterior.



**Figure 16** Imaging in 24-week fetus with primitive right pulmonary hypoplasia and persistence of left superior vena cava (LSVC). (a) In four-chamber view, heart is shifted to the right and its axis deviated to the middle (mesocardia). One lobe of right lung is not visible in front of heart. (b) Three-vessel view displays disproportion in size between left (LPA) and right (RPA) pulmonary arteries, LPA being larger. There is also persistent LSVC, to left of pulmonary artery (PA). Right superior vena cava (RSVC) is in its usual place, to right of aorta (Ao). (c) Three-vessel-and-trachea view seems normal, without any major disproportion between ductal and aortic arches. Ant, anterior; DA, ductus arteriosus; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle; T, trachea.

assess PA anomalies, the entire cardiac anatomy should be evaluated in the 4CV, the RVOT and the 3V and 3VT views. The use of color and pulsed Doppler can be key in the evaluation of PA anomalies. When assessing a fetus with a PA anomaly, the 3V and 3VT views complement each other: we highlight the need to use both and to differentiate between them, and stress that normality of one view does not exclude abnormality of the other.

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## SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:



**Figure S1** Early stages of heart development.

**Figure S2** Normal development of semilunar valve. Semilunar valves are produced by division of the truncus arteriosus during development. Between day 23 and day 35, growth of superior, inferior and lateral endocardial cushions allows separation of the common atrioventricular canal, which becomes the roots of both the aortic and pulmonary trunks (between days 42 and 49).

**Figure S3** Normal development of aortic arches.

**Table S1** Typical findings of congenital pulmonary artery anomalies, with illustrated examples of cases<sup>2,3,31–42</sup> (Figures 5–16)